



Infrared Observations with the New Solar Telescope

Philip Goode
NEW JERSEY INST OF TECH NEWARK

05/21/2015
Final Report

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REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 10-06-2015		2. REPORT TYPE Final Performance		3. DATES COVERED (From - To) 01-04-2012 to 31-03-2015		
4. TITLE AND SUBTITLE Infrared Observations with the 1.6 Meter New Solar Telescope in Big Bear: Origins of Space Weather				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER FA9550-12-1-0066		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Philip Goode				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NEW JERSEY INST OF TECH NEWARK 323 MARTIN LUTHER KING JR BLVD NEWARK, NJ 07102-1982 US				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AF Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT A DISTRIBUTION UNLIMITED: PB Public Release						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT <p>The work reported here utilized the 1.6 m clear aperture solar telescope in Big Bear Lake, CA. This telescope is the largest aperture and most powerful solar telescope ever built, which enable the high resolution observations essential to our new results discussed here. The telescope enables a fundamental probing of the origins of space weather. Under current AFOSR support, the NST was used to observe the photosphere, chromosphere and up to the transition region of the Sun with unprecedented resolution to elucidate the fundamental nature of the dynamics of solar magnetism and its evolution. We use the NST in sustained campaigns, which has been at the core of BBSO's ability to provide unique data in support of the community's efforts to understand our star and its environs. Observing campaigns are essential to determine the origin of 'space weather', which arises from solar magnetic storms and can have deleterious effects on satellites, as well as the terrestrial power grid, telecommunications, and other aspects of human civilization.</p>						
15. SUBJECT TERMS solar storms, coronal mass ejections, solar activity, solar flares, New Solar Telescope, IRIM						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Philip Goode	
U	U	U	UU		19b. TELEPHONE NUMBER (Include area code) 973-596-3565	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Report: FA9550-12-0066
Start Date 4/1/2012
End Date 3/31/2015
PI: Philip Goode

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In January 2009, BBSO attained first light with its off-axis, 1.6 m clear aperture New Solar Telescope (NST). First diffraction limited observations with the NST came in the Summer of 2009, while the first observations corrected by adaptive optics (AO) came in the Summer of 2010 and first vector magnetograms (VMGs) in the Summer of 2011. In 2012, a new generation of solar adaptive optics (AO) developed in Big Bear led to hitherto only imagined resolution for studies of the origin of space weather. The new AO enables light from the off-axis, 1.6 m clear aperture New Solar Telescope (NST) to be corrected at the bluest of visible wavelengths under nominal seeing. In practice, the telescope has twice the spatial resolution of any other solar telescope in the world and enables us to resolve the fundamental scale of solar dynamics. That is, the photon mean free path in the photosphere is about 100 km, and the NST is the only telescope the can resolve these wavelengths from the Sun. For the next several years, the NST will be the only telescope in the US that can make such high resolution observations. We have taken visible light vector magnetograms for the first time with the NST. The NST is the first facility class solar telescope built in the U.S. in a generation.

Under current AFOSR support, the NST was used to observe the photosphere, chromosphere and up to the transition region with unprecedented resolution to elucidate the fundamental nature of the dynamics of solar magnetism and its evolution. We use the NST in sustained campaigns, which has been at the core of BBSO's ability to provide unique data in support of the community's efforts to understand our star and its environs. Observing campaigns are essential to determine the origin of "space weather", which arises from solar magnetic storms and can have deleterious effects on satellites, as well as the terrestrial power grid, telecommunications, and other aspects of human civilization.

Data requests come to BBSO on a daily basis from around the world. The NST generates far more data than the old BBSO telescope. This has presented a more challenging problem for archiving and community access. To facilitate broader use of NST data, all the data are placed online in a user friendly way . Users of NST data are only asked to acknowledge BBSO in their resulting publications.

FA9550-12-0066 has supported Eun-Kyung Lim (who now has a tenured research position at the Korean Astronomy and Space Science Institute in her native Korea), Vasyl Yurchyshyn (who leads our long standing collaboration with Korean scientists and does first processing of NST data) and Kwangsu Ahn (an instrumental scientist in BBSO who works on spectro-polarimeters). This AFOSR support has been essential for our successes.

Research Highlights:

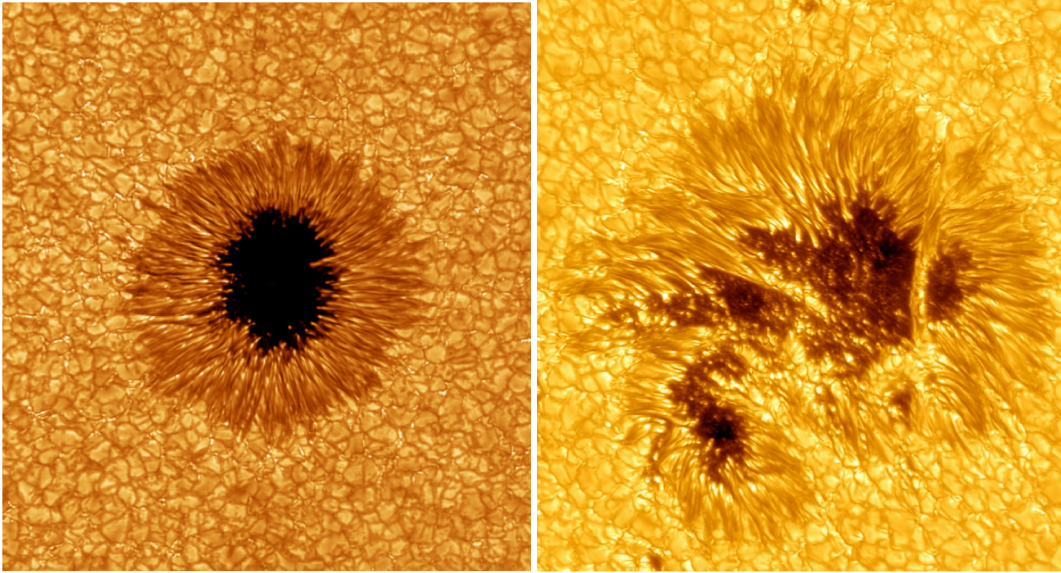
1)Research Highlight: Plasma Injections into Magnetic Loops – new and fundamental insights into the long-standing problem of coronal heating. It has been argued that Alfvén waves (Alfvén 1947), nanoflare magnetic energy release events driven by photospheric convective motion (Parker 1988), and even granular acoustic noise (Schwarzschild 1948) are responsible for coronal heating. Despite many studies (e.g. Aschwanden, Nightingale & Alexander, 2000; van Ballegoijen et al. 2011 and references therein) over the years, the mechanism of the energy transport from the photosphere to the corona remains elusive. In Ji, Cao and Goode (2012), we combined NST data with data from the AIA/SDO satellite data to report the first direct observations of dynamical events originating in the Sun's cool photosphere and subsequently lighting up the corona.

We find continuous impulsive plasma injections along the ultrafine magnetic structures from their footpoint regions, which fade away along the loop systems. We further find that the more intense of these ejecta also are observed in simultaneous H α blue wing images. The loops emerge from the intergranular lanes and rise up the base of the corona. These loops are an order magnitude cooler and narrower than ordinary coronal loops. They haven't been seen before!

The narrow (100-200 km across) magnetic bright points (BPs) are overwhelmingly concentrated in the intergranular lanes from which the ejecta arise. That is, such lanes are the regions of magnetic loop footpoints, which are virtually absent elsewhere. In the footpoint regions of the ultrafine magnetic loop system, we also see that the outflow is underneath the mesh-like EUV emission patches called "moss" (Berger et al. 1999), which are areas where coronal loops are anchored. In the regions with fewer photospheric BPs, we see similar, but sparsely distributed injections of the 1083 nm absorbing plasma from the intergranular lanes. The 10830 nm line spans from the photosphere up to the base of the corona, but is concentrated in the upper chromosphere. High-resolution observations of the solar atmosphere with the NST reveal that plasma injections associated with the ultrafine magnetic loop structures originate from compact magnetic flux concentrations in the intergranular lanes on the surface and reach up to the solar corona. The continuous, pulsing plasma ejections along the magnetic structures also cause essentially simultaneous, spatially co-aligned

local impulsive coronal heating events seen with AIA/SDO. See Ji, Cao and Goode (2012), as well as supplemental proposal material (images and movies) at <http://www.bbso.njit.edu/2012AGS> , for more details of the observed 1083 nm (near-IR) injections and their progress from the intergranular lanes through the chromosphere and into the coronal lines seen in various AIA/SDO lines. These observations suggest that at least some of the solar energy that heats the corona is channeled through the ultrafine magnetic loop structures in the form of plasma ejecta. The observations of Ji, Cao and Goode (2012) lacked vector magnetograms (VMGs), so we could only guess the precise role of the magnetic field. In the second year of this AFOSR support, we plan to expand our data collection to include simultaneous VMGs, as well as performing modeling of NST data to uncover the mechanism of the ejections. Such critical results hold the key to understanding the dynamics of the changing magnetic field that causes the ejecta from the intergranular lanes that rise up to heat the corona.

2) New insight into the formation of sunspots Sunspot formation has been one of the great solar mysteries upon which the NST has yield key information. Our concentration of sunspots in the second year of funding arises because of the improved resolution derived from the new AO system. In the side-by-side images below, one sees on the left a sunspot from seen from the NST in 2010 with the old AO system. This sunspot image was called the best sunspot image ever by the French magazine Ciel et Espace. The sunspot on the right was taken in 2013 at the same wavelength with a slightly smaller field of view, but with the new AO. The 2010 and 2013 images were taken under comparable seeing conditions, but the vast improvement in the right hand image below is apparent. The light bridge shows twists in it, finer structures in the penumbra are apparent, and the umbral dots are much more apparent. In fact, many of the umbral dots show tiny black dots at their centers. These black dots are smaller than 0".1 (or 70 km) in diameter, so the NST is now resolving the fundamental scale of solar dynamics. The black dots arise from the central part of the umbral dot being at a higher altitude at which it is cooler (hence darker) than its surroundings.



Under the first year of current AFOSR support, the NST was used to observe the photosphere, chromosphere and up to the transition region with unprecedented resolution to elucidate the fundamental nature of the dynamics of solar magnetism and its evolution. In the second year, we concentrated on the nature of sunspots and sunspot formation. As always, we use the NST in sustained campaigns, which has been at the core of BBSO's ability to provide unique data in support of the community's efforts to understand our star and its environs. Observing campaigns are essential to determine the origin of "space weather", which arises from solar magnetic storms and can have deleterious effects on satellites, as well as the terrestrial power grid, telecommunications, and other aspects of human civilization.

In some detail, the presence of a penumbra is one of the main properties of a mature sunspot, but its formation mechanism has been elusive due to a lack of observations that fully cover the formation process. Utilizing the NST, Lim, Yurchyshyn, Goode and Cho (ApJLett, 2013, 767, 18) observed the formation of a partial penumbra for about 7 hr simultaneously at the photospheric (TiO ; 7057 Å) and the chromospheric ($\text{H}\alpha$ - 1 Å) spectral lines with high spatial and temporal resolution. From this uninterrupted, long observing sequence, we found that the formation of the observed penumbra was closely associated with flux emergence under the pre-existing chromospheric canopy fields. Based on this finding, we suggested a possible scenario for penumbra formation in which a penumbra forms when the emerging flux is constrained from continuing to emerge, but rather is trapped at the photospheric level by the overlying chromospheric canopy fields.

Recent observations of a sunspot's umbra have suggested that it may be finely structured on a subarcsecond scale representing a mix of hot and cool plasma elements. In this study, Yurchyshyn, Abramenko, Kosovichev and Goode (ApJ, 2014, 787, 58) report the first detailed observations of umbral spikes, which are

cool jet-like structures seen in the chromosphere of an umbra. The spikes are cone-shaped features with a typical height of 0.5-1.0 Mm and a width of about 0.1 Mm. Their lifetime ranges from 2 to 3 minutes and they tend to re-appear at the same location. The spikes are not associated with photospheric umbral dots and they instead tend to occur above the darkest parts of the umbra where magnetic fields are strongest. The spikes exhibit up and down oscillatory motions and their spectral evolution suggests that they might be driven by upward propagating shocks generated by photospheric oscillations. It is worth noting that triggering of the running penumbral waves seems to occur during the interval when the spikes reach their maximum height.

The 1.6 m clear aperture solar telescope in Big Bear is operational and with its adaptive optics (AO) system it provides diffraction limited solar imaging and polarimetry in the near-infrared (NIR). While the AO system was being upgraded to provide diffraction limited imaging at bluer wavelengths, the instrumentation and observations were concentrated in the NIR. The New Solar Telescope (NST) operates in campaigns, making it the ideal ground-based telescope to provide complementary/supplementary data to SDO and Hinode. The NST makes photometric observations in H α (656.3 nm) and TiO (705.6 nm) among other lines. As well, the NST collects vector magnetograms in the 1565 nm lines and is beginning such observations in 1083.0 nm. Here, Cao and Goode (Solar Phys., 2013, 287, 315) discussed the relevant NST instruments, including AO, and present some results that are germane to NASA solar missions.

3) *Dynamics in Sunspot Umbra as Seen in New Solar Telescope and Interface Region Imaging Spectrograph Data.* In figure below we show a sample of NST and IRIS data acquired during a joint IRIS-BBSO observational campaign. Here, the power spectrum plots based on intensity profiles of IRIS spectra indicate that the strength of shocks inside the umbra varies along the slit as well as with height. Data also suggest that propagation of wave energy into the sunspot's atmosphere may be governed by such factors as structure and topology of the associated magnetic fields.

We also traced and plotted all the locations where umbral flashes (UFs) occurred in the sunspot umbra. We find that all UFs structures appeared in a form of bright lanes of various length, as opposed to being diffuse patches randomly distributed in the umbra. We also These UFs lanes tend to run along the sunspot light bridges and clusters of bright umbral dots. In other words, these are locations with enhanced magneto-convection features and larger (as compared to the dark umbra) gradients of the magnetic fields. At the edge of these convection cells the umbral field weakens and expands rapidly, while the cells themselves rise above the dark umbra. It is interesting to note that the bright UF lanes tend to appear on that side of light bridges that face the center of the umbra.

Such dynamics suggests that UFs may be linked to a presumed horizontal trans-umbral wave that causes UFs to sequentially appear at progressively

distant light bridges. The intensity of shocks is not uniform over the umbra and the most intense shock structures were detected in the parts of the umbra associated with one of the LBs. We suggest that the non-homogeneities in the umbral magnetic field may play an important role in heating coronal loops rooted in the sunspots by facilitating generation of shocks. The non-uniformities may also increase

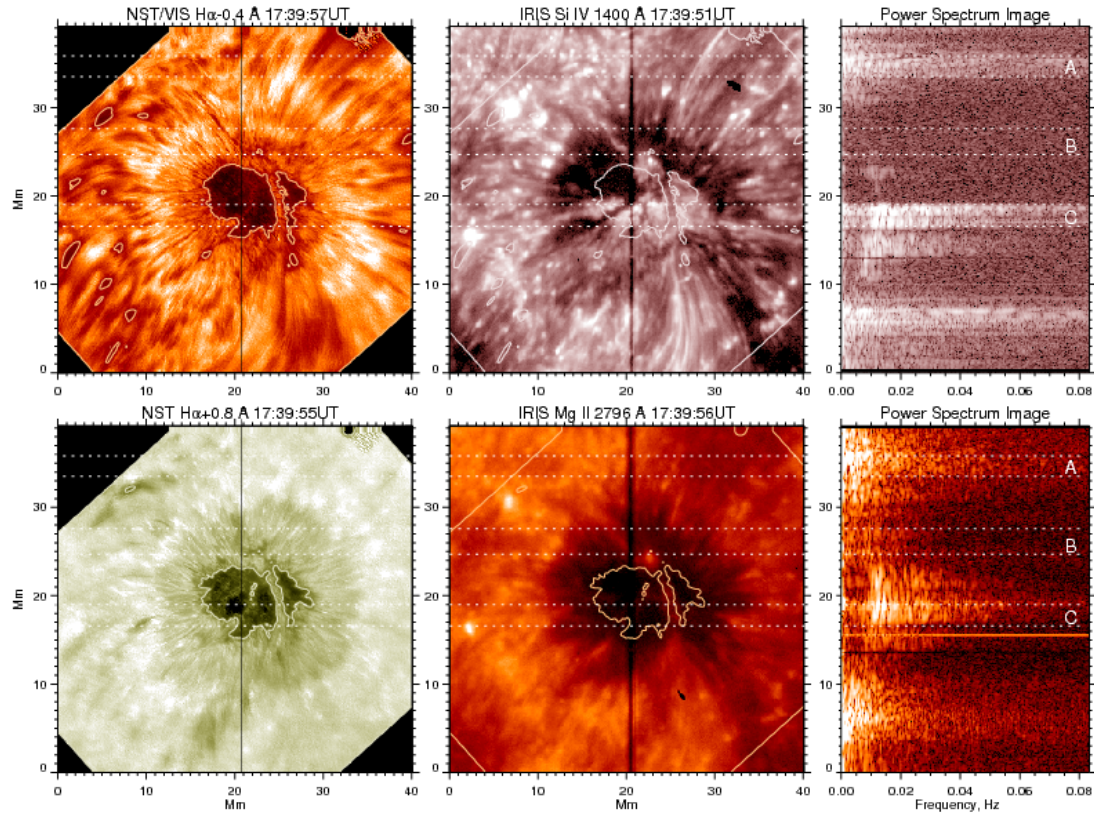


Figure 1. NST H-alpha (left), IRIS slit-jaw images (center) and IRIS power spectra images (right). The vertical line across chromospheric images marks the location of the IRIS slit. The three sets of horizontal dotted lines outline areas A, B, and C selected for analysis. The power spectra image is a spatial stack of many power spectra calculated at each pixel position along the IRIS slit using intensity time profiles. The contours outline H-alpha umbra and are shown here to ease the comparison.

effectiveness of fast to slow mode conversion, however this question has to be answered by future MHD simulations.

4) Kinematics of Solar Chromospheric Surges of AR 10930. Solar chromospheric surges are often reported to contain rotational motion. However, the details of the motion and driving mechanism of the surges are not yet fully understood. Recurrent surges with rotational motion at AR 10930 on the west limb are observed by Hinode Solar Optical Telescope (SOT) continuously from 11:21 UT on December 18 to 09:58 UT on December 19, 2013, using the Ca II H

broadband filter. We analyzed details of the motion including number of turns from the rise of the surge to the fall, axial speed and acceleration. During the observation, rise and fall motion accompanying rotation appears recurrently. There occur a total of 14 surges at AR 10930 over 17 hours. The average duration is 45 minutes, and the average width, and length are 8 Mm, and 39 Mm, respectively. We speculate that the surges occurred by recurrent reconnection events between the twisted prominence and large untwisted flux tube.

5) *NST Observations of a slow rise x1.6 flare.* On November 7, 2014 NST observed an X1.6 flare from the beginning to the end. This flare led to an eruption of a flux rope and was associated with a fast coronal mass ejection that are known to cause strong geomagnetic disturbances. The rise phase of the flare's X-ray emission was unusually extended to about 40 min, which allowed us to focus on details of the flare development. We detected at least 4 reconnection episodes occurring in the rise phase and which resulted in formation of a large eruptive flux rope out of several separate and stable twisted loops systems. The data also clearly demonstrates that the flare was triggered by emergence of magnetic fields within the umbrae of a delta-sunspot. This "slow-motion" flare illuminates many hidden before details on the development of eruptive events.

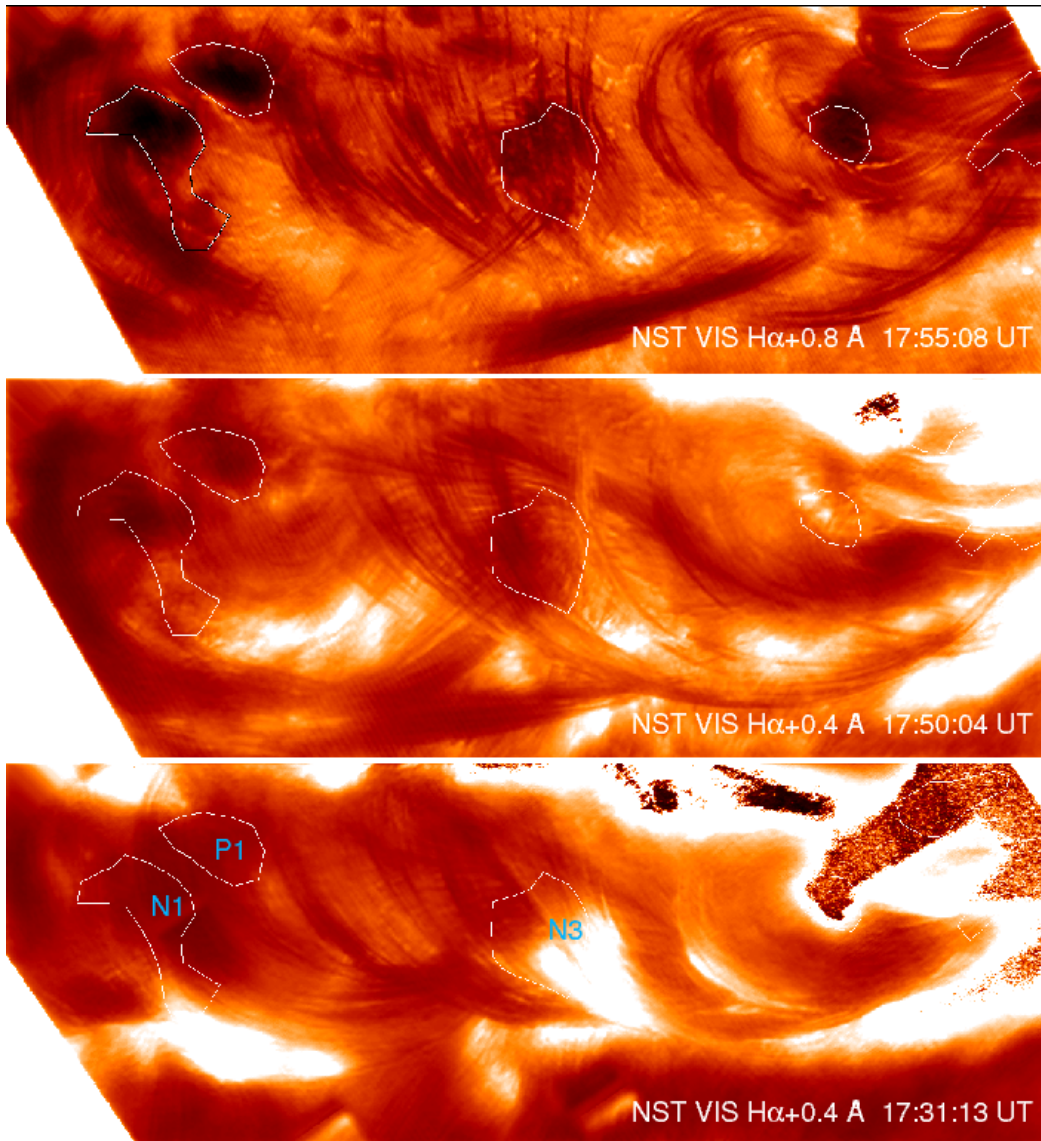


Figure 2. Evolution of the Post-Eruption Arcade (PEA, dark narrow loop system) during the x1.6 flare on Nov 7, 2014. Note that during the pick of the flare at 17:30UT the PEA is already visible, which is only one indication that this slow-rise flare consisted of several reconnection and flux formation events.

BBSO Publications Supported by AFOSR FA9550-12-0066:

Dynamics of Chromospheric Upflows and Underlying Magnetic Fields, 2013, V. Yurchyshyn, V. Abramenko, P.R. Goode, ApJ, 767, 17

Turbulent Pair Dispersion of Photospheric Bright Points, 2012, F. Lepreti, V. Carbone, V.I. Abramenko, V. Yurchyshyn, P.R. Goode, V. Capparelli, V. Vecchio, ApJLett, 759, L17

Observation of Ultrafine Channels of Solar Corona Heating, 2012, H. Ji, W. Cao, P.R. Goode, ApJLett, 750, L25

New Solar Telescope in Big Bear: Evidence for Super-Diffusivity and Small-Scale Solar Dynamos, P.R. Goode, V. Abramenko, V. Yurchyshyn, 2012, Phys. Scr., 86, 018402

Observation of a Non-radial Penumbra in a Flux Emerging Region under Chromospheric Canopy Fields, 2013, E.-K. Lim, V. Yurchyshyn, P.R. Goode, K.S. Cho, ApJLett, 767, 18

High Resolution Observations of Chromospheric Jets in Sunspot Umbra, 2014, V. Yurchyshyn, V. Abramenko, A. Kosovichev, P.R. Goode, ApJ 787, 58

Infrared Observations from the New Solar Telescope at Big Bear, 2013, Solar Phys. 287, 315-322, W. Cao, P.R. Goode

Dynamics in Sunspot Umbra as Seen in New Solar Telescope and Interface Region Imaging Spectrograph Data, by Yurchyshyn, V., Abramenko, V., and Kilcik, A., 2015, Astrophys. J., 798/2, article id. 136

Kinematics of Solar Chromospheric Surges of AR 10930, by Bong, S.-C., Cho, K.-S., and Yurchyshyn, V., 2014, J. Korean Astron. Soc., 47/6, pp. 311-317.

NST Observations of a slow rise X1.6 flare, by Yurchyshyn, V., and Kumar, P., 2015, in preparation

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1.

1. Report Type

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908-249-1943

Organization / Institution name

New Jersey Institute of Technology

Grant/Contract Title

The full title of the funded effort.

Infrared Observations with the 1.6 Meter New Solar Telescope in Big Bear: Origins of Space Weather

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0066

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Philip R. Goode

Program Manager

The AFOSR Program Manager currently assigned to the award

Kent Miller

Reporting Period Start Date

04/01/2012

Reporting Period End Date

3/31/2015

Abstract

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